

Efficient electronic entanglement concentration assisted with single mobile electron

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We present an efficient entanglement concentration protocol (ECP) for mobile electrons with charge detection. This protocol is quite different from other ECPs for one can obtain a maximally entangled pair from a pair of less-entangled state and a single mobile electron with a certain probability. With the help of charge detection, it can be repeated to reach a higher success probability. It also does not need to know the coefficient of the original less-entangled states. All these advantages may make this protocol useful in current distributed quantum information processing.

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Entanglement plays an important role in the current quantum communication [1–14] and distributed quantum information processing field [15–19]. For most of the practical quantum communication and computation protocols, people need to share a maximally entangled state with each other. However, the entanglement resource is fragile, for the maximally entangled state may be degraded into a mixed state or become a less-entangled state when it interacts with the noisy environment. People usually resort to the entanglement purification [20–33] to increase the fidelity of the mixed state and the entanglement concentration [34–46] which will be detailed here to recover the less-entangled state to a maximally entangled state. Currently, most of the protocols for purification and concentration are focused on optical systems [22–28, 30–32, 36–42, 44], for during the transmission, the photons have weak interaction with the environment.

On the other hand, there is another candidate for the flying qubit, that is the mobile electron. A strong interaction between different electrons makes them feasible to interact flying electron spins with other solid electron spins, since the coulomb interaction between each electrons is strongly screened. In the recent years, the investigation about the flying electron qubits becomes an active study area [47–53]. In 2004, Beenakker *et al.* broke through the obstacle of the no-go theorem with the help of charge detection and constructed a controlled-NOT(CNOT) gate using beam splitters and spin rota-

tions near deterministically [47]. With the help of charge detector, people can construct the charge qubit [53], perform entanglement purification [33], construct entangled spins [54], and prepare a multipartite entanglement analyzer and cluster states [55]. Especially, the flying qubit can also be used in the one dimensional system and create entanglement between two distant matter qubits. Recently, Matsuzaki and Jefferson proposed a protocol for distributed quantum information processing with mobile electrons [52]. In their protocol, they used mobile electron spins as the mediators of the interaction between the static qubits at each node and finally created a high quality entanglement between each node. Unfortunately, the distributed quantum entanglement may also be degraded into the less-entangled state when it is coupled with the noisy environment. On the other hand, with current technology, it is difficult to operate each flying qubits perfectly, which can also lead the ideal maximally entangled state to be degraded [52].

Entanglement concentration is a powerful tool to recover a less-entangled state into a maximally entangled one with only local operation and classical communication. The first entanglement concentration protocol (ECP) was proposed by Bennett *et al.* in 1996 [34]. This method is called Schmidt projection method, in which they need the collective measurement and need to know the exact coefficient of the initial entangled state. In 2001, Zhao *et al.* and Yamamoto *et al.* proposed two similar simplified ECPs with linear optical elements based on the Schmidt projection method respectively. Both ECPs have been realized experimentally [39, 40]. In 2009, we proposed an ECP based on electrons [43]. Almost all the current ECPs need two pairs of less-entangled states,

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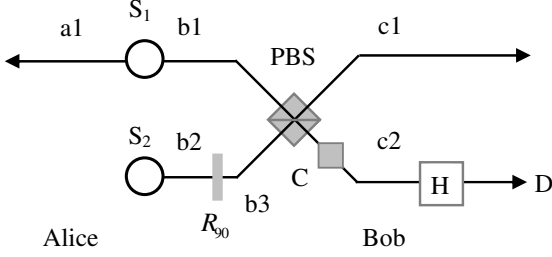


FIG. 1: The schematic drawing of the principle of our ECP based on charge detection. Only one pair of less-entangled state and a single electron are required here. PBS can fully transmit spin up $|\uparrow\rangle$ and reflect spin down $|\downarrow\rangle$. The charge detector (C) can distinguish the charge number 1 from 0 and 2, but can not distinguish the number 0 and 2. D is the detector.

but after performing each ECP, at most one pair of maximally entangled state can be obtained with a certain success probability.

Actually, using two copies of less-entangled pairs to obtain one maximally entangled pair is not the optimal way. In this paper, we show that we can perform the ECP with the same success probability by using only one pair of less-entangled state and a single electron. Compared with the previous ECPs, this protocol requires less less-entangled resources. Moreover, analogized with the Ref. [43], we adopt the charge detectors and polarization beam splitter (PBS) to reconstruct our protocol, which makes it have a higher success probability than those protocols with linear optics. This protocol can also be used to concentrate the multipartite entangled system. All these advantages may make this protocol more useful in current quantum communication and distributed quantum information processing.

Before we start to explain our ECP, we first introduce the charge detector (C) which is a key element shown in Fig. 1. The charge detector can distinguish the occupation number 1 from the occupation number 0 and 2. However, it can not distinguish between the occupation number 0 and 2 [47], so in both two cases, we define the charge detector will show 0 for simple. In Fig.1, we suppose the source S_1 emits a pair of less-entangled state of the form

$$|\Phi\rangle_{a1b1} = \alpha|\uparrow\rangle_{a1}|\uparrow\rangle_{b1} + \beta|\downarrow\rangle_{a1}|\downarrow\rangle_{b1}. \quad (1)$$

Here $|\alpha|^2 + |\beta|^2 = 1$. $|\uparrow\rangle$ and $|\downarrow\rangle$ are spin up and spin down respectively. Meanwhile, the source S_2 emits a single electron to Bob of the form

$$|\Phi\rangle_{b2} = \alpha|\uparrow\rangle_{b2} + \beta|\downarrow\rangle_{b2}. \quad (2)$$

Bob receives two electrons from the spatial modes $b1$ and $b2$ and Alice only receives one electron from $a1$. Bob first

performs a bit-flip operation and makes $|\Phi\rangle_{b2}$ become

$$|\Phi\rangle_{b2} \rightarrow |\Phi\rangle_{b3} = \alpha|\downarrow\rangle_{b3} + \beta|\uparrow\rangle_{b3}. \quad (3)$$

Therefore, the original entangled state of the three-electron state can be written as

$$\begin{aligned} |\Psi\rangle &= |\Phi\rangle_{a1b1} \otimes |\Phi\rangle_{b3} \\ &= (\alpha|\uparrow\rangle_{a1}|\uparrow\rangle_{b1} + \beta|\downarrow\rangle_{a1}|\downarrow\rangle_{b1}) \otimes (\alpha|\downarrow\rangle_{b3} + \beta|\uparrow\rangle_{b3}) \\ &= \alpha^2|\uparrow\rangle_{a1}|\uparrow\rangle_{b1}|\downarrow\rangle_{b3} + \beta^2|\downarrow\rangle_{a1}|\downarrow\rangle_{b1}|\uparrow\rangle_{b3} \\ &\quad + \alpha\beta(|\uparrow\rangle_{a1}|\uparrow\rangle_{b1}|\uparrow\rangle_{b3} + |\downarrow\rangle_{a1}|\downarrow\rangle_{b1}|\downarrow\rangle_{b3}). \end{aligned} \quad (4)$$

Then Bob lets his two electrons pass through the PBS, which fully transmits $|\uparrow\rangle$ and reflects $|\downarrow\rangle$. The $|\Psi\rangle$ becomes

$$\begin{aligned} |\Psi\rangle &\rightarrow |\Psi'\rangle = \alpha^2|\uparrow\rangle_{a1}|\uparrow\rangle_{c2}|\downarrow\rangle_{c2} + \beta^2|\downarrow\rangle_{a1}|\downarrow\rangle_{c1}|\uparrow\rangle_{c1} \\ &\quad + \alpha\beta(|\uparrow\rangle_{a1}|\uparrow\rangle_{c1}|\uparrow\rangle_{c2} + |\downarrow\rangle_{a1}|\downarrow\rangle_{c1}|\downarrow\rangle_{c2}). \end{aligned} \quad (5)$$

From above equation, one can find that the item $|\uparrow\rangle_{a1}|\uparrow\rangle_{c2}|\downarrow\rangle_{c2}$ means that the two electrons in Bob's location are both in the spatial mode $c2$ while the item $|\downarrow\rangle_{a1}|\downarrow\rangle_{c1}|\uparrow\rangle_{c1}$ means that the two electrons are both in the mode $c1$. However, both the items $|\uparrow\rangle_{a1}|\uparrow\rangle_{c1}|\uparrow\rangle_{c2}$ and $|\downarrow\rangle_{a1}|\downarrow\rangle_{c1}|\downarrow\rangle_{c2}$ mean that the two electrons are in the modes $c1$ and $c2$, respectively. Therefore, the charge detector will show 0 if the original state collapses to $|\uparrow\rangle_{a1}|\uparrow\rangle_{c2}|\downarrow\rangle_{c2}$ or $|\downarrow\rangle_{a1}|\downarrow\rangle_{c1}|\uparrow\rangle_{c1}$, And it will show 1 if the original state collapses to

$$|\Psi''\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle_{a1}|\uparrow\rangle_{c1}|\uparrow\rangle_{c2} + |\downarrow\rangle_{a1}|\downarrow\rangle_{c1}|\downarrow\rangle_{c2}). \quad (6)$$

The probability of obtaining the state of Eq. (6) is $2|\alpha\beta|^2$. Obviously, it is the three-electron maximally entangled state. It is easy to get a two-electron maximally entangled state from Eq. (6). Bob needs to perform a Hadamard operation on his electron in the mode $c2$. It makes

$$\begin{aligned} |\uparrow\rangle_{c2} &\rightarrow \frac{1}{\sqrt{2}}(|\uparrow\rangle_{c2} + |\downarrow\rangle_{c2}), \\ |\downarrow\rangle_{c2} &\rightarrow \frac{1}{\sqrt{2}}(|\uparrow\rangle_{c2} - |\downarrow\rangle_{c2}). \end{aligned} \quad (7)$$

After Bob performing the Hadamard operation, Eq. (6) becomes

$$\begin{aligned} |\Psi''\rangle &\rightarrow \frac{1}{2}[|\uparrow\rangle_{a1}|\uparrow\rangle_{c1}(|\uparrow\rangle_{c2} + |\downarrow\rangle_{c2}) \\ &\quad + |\downarrow\rangle_{a1}|\downarrow\rangle_{c1}(|\uparrow\rangle_{c2} - |\downarrow\rangle_{c2})] \\ &= \frac{1}{2}[(|\uparrow\rangle_{a1}|\uparrow\rangle_{c1} + |\downarrow\rangle_{a1}|\downarrow\rangle_{c1})|\uparrow\rangle_{c2} \\ &\quad + (|\uparrow\rangle_{a1}|\uparrow\rangle_{c1} - |\downarrow\rangle_{a1}|\downarrow\rangle_{c1})|\downarrow\rangle_{c2}]. \end{aligned} \quad (8)$$

Then the last step for Bob is to measure the spin in the basis $Z = \{|\uparrow\rangle, |\downarrow\rangle\}$. From above equation, if the measurement result is $|\uparrow\rangle_{c2}$, the electron pair in the modes $a1c1$ will become

$$|\phi^+\rangle_{a1c1} = \frac{1}{\sqrt{2}}(|\uparrow\rangle_{a1}|\uparrow\rangle_{c1} + |\downarrow\rangle_{a1}|\downarrow\rangle_{c1}). \quad (9)$$

If the measurement result is $|\downarrow\rangle_{c2}$, the electron pair in the modes $a1c1$ will become

$$|\phi^-\rangle_{a1c1} = \frac{1}{\sqrt{2}}(|\uparrow\rangle_{a1}|\uparrow\rangle_{c1} - |\downarrow\rangle_{a1}|\downarrow\rangle_{c1}). \quad (10)$$

Bob only needs to perform a phase-flip operation on his electrons to get the $|\phi^+\rangle_{a1c1}$. If they share the pair $|\phi^\pm\rangle_{a1c1}$, Bob will tell Alice that the protocol is successful and asks Alice to retain her electron. In this way, they can share a maximally entangled state from a less-entangled state with the success probability of $2|\alpha\beta|^2$.

From above description, Bob chooses the case that the charge detector's result is 1 and discards the case of 0. It is essentially the partially parity check gate which picks up the even parity states $|\uparrow\rangle|\uparrow\rangle$ and $|\downarrow\rangle|\downarrow\rangle$ but discards the odd parity states $|\uparrow\rangle|\downarrow\rangle$ and $|\downarrow\rangle|\uparrow\rangle$. In this case, the function of PBS is similar as it is in the optical systems [36, 38]. In Refs. [36, 38], they need to check that both the output modes of the optical PBS contain exactly and only contain one photon. It is so called the post-selection principle. Therefore, even if they successfully perform their ECPs, the maximally entangled state would be destroyed by the single photon detector. The maximally entangled photon pair can not be remained for further application. In this protocol, Bob can judge the successful case from the charge detection results. The charge qubit carries both the spin degree of freedom and the charge degree of freedom. As charge and spin are commute and a measurement of charge leaves the spin qubit unaffected, the charge detection does not affect the entangled state of the electrons.

Actually, the charge detector and PBS are more powerful than it has been described above, for the discarded items are essentially the lesser-entangled state which can be reconcentrated in a second step. That is to say, we can not only pick up the even parity states, but also pick up the odd parity states. In Fig. 2, we add another PBS say PBS_2 to reconstruct our ECP. We denote the whole setup P gate shown in Fig. 2. If the charge detector's result is 0, the original state will collapse to

$$|\Psi\rangle''' = \alpha^2|\uparrow\rangle_{a1}|\uparrow\rangle_{c2'}|\downarrow\rangle_{c2'} + \beta^2|\downarrow\rangle_{a1}|\downarrow\rangle_{c1'}|\uparrow\rangle_{c1'} \quad (11)$$

It means that after passing through the PBS_1 , both the two electrons are in the same spatial mode, while with the help of PBS_2 , they are coupled into

$$|\Psi\rangle''' = \alpha^2|\uparrow\rangle_{a1}|\uparrow\rangle_{c1}|\downarrow\rangle_{c2} + \beta^2|\downarrow\rangle_{a1}|\downarrow\rangle_{c1}|\uparrow\rangle_{c2}. \quad (12)$$

It means that the two electrons in Bob's location are in the different spatial modes, say $c1$ and $c2$, respectively. Then after performing the Hadamard operation and measuring the spin of the electron on the mode $c2$, they can get

$$|\Phi\rangle_1 = \alpha^2|\uparrow\rangle_{a1}|\uparrow\rangle_{c1} + \beta^2|\downarrow\rangle_{a1}|\downarrow\rangle_{c1}, \quad (13)$$

if the measurement result is $|\uparrow\rangle$. They can get

$$|\Phi\rangle_2 = \alpha^2|\uparrow\rangle_{a1}|\uparrow\rangle_{c1} - \beta^2|\downarrow\rangle_{a1}|\downarrow\rangle_{c1}, \quad (14)$$

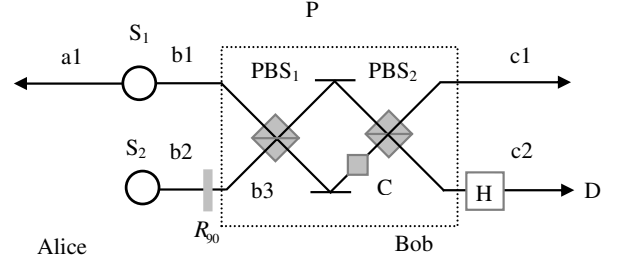


FIG. 2: The schematic drawing of the principle of reconstructing of our ECP. If the measurement result of charge detector is 0, the remaining lesser-entangled pair can also be reused to perform the entanglement concentration. Another PBS says PBS_2 is used to couple the state into the same spatial mode. P denotes that it plays essentially the role of the parity check gate.

if the measurement result is $|\downarrow\rangle$. Both Eqs. (13) and (14) are lesser-entangled states. They can be reconcentrated in the next step. Briefly speaking, if they obtain $|\Phi\rangle_1$, Bob needs to choose another single electron of the form

$$|\Phi\rangle'_{b2} = \alpha^2|\uparrow\rangle_{b2} + \beta^2|\downarrow\rangle_{b2}. \quad (15)$$

After rotating it with R_{90} , it becomes

$$|\Phi\rangle'_{b3} = \alpha^2|\downarrow\rangle_{b3} + \beta^2|\uparrow\rangle_{b3}. \quad (16)$$

Then the three-electron system evolves as

$$\begin{aligned} |\Phi\rangle_2 \otimes |\Phi\rangle'_{b3} &= (\alpha^2|\uparrow\rangle_{a1}|\uparrow\rangle_{c1} + \beta^2|\downarrow\rangle_{a1}|\downarrow\rangle_{c1}) \\ &\otimes (\alpha^2|\downarrow\rangle_{b3} + \beta^2|\uparrow\rangle_{b3}) \\ &= \alpha^4|\uparrow\rangle_{a1}|\uparrow\rangle_{c1}|\downarrow\rangle_{b3} + \beta^4|\downarrow\rangle_{a1}|\downarrow\rangle_{c1}|\uparrow\rangle_{b3} \\ &+ \alpha^2\beta^2(|\uparrow\rangle_{a1}|\uparrow\rangle_{c1}|\uparrow\rangle_{b3} + |\downarrow\rangle_{a1}|\downarrow\rangle_{c1}|\downarrow\rangle_{b3}). \end{aligned} \quad (17)$$

Obviously, if the charge detection $C=1$, they can obtain the same three-electron state as described in Eq. (6) with a probability of $2|\alpha\beta|^4$. Otherwise, if $C=0$, the remained state is a lesser-entangled state and can be reconcentrated in a third round. In this way, they can repeat this protocol to get a higher success probability than other protocols.

It is straightforward to extend this protocol to multipartite pure entangled state systems. An N -electron less-entangled system can be described as

$$|\Phi\rangle_N = \alpha|\uparrow\rangle_1|\uparrow\rangle_2 \cdots |\uparrow\rangle_N + \beta|\downarrow\rangle_1|\downarrow\rangle_2 \cdots |\downarrow\rangle_N. \quad (18)$$

The N electrons are emitted from S_1 and sent to N parties, say, Alice, Bob, Charlie, etc., as shown in Fig. 3. Alice gets the electron of number 1 in the spatial mode $a1$. Bob gets number 2 in the spatial mode $b1$ and Charlie gets the number 3, etc. The source of S_2 also emits a single electron to Bob with the same form of Eq. (2). After rotating it by 90° , the composite system can be described as

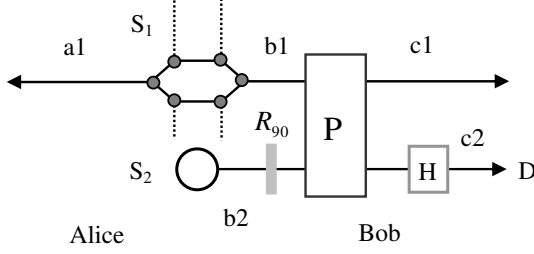


FIG. 3: Schematic diagram of the multipartite entanglement concentration protocol. N particles in the multipartite GHZ state from the source S_1 are sent to N parties, say, Alice, Bob, Charlie, etc. The source S_2 also emits a single electron to Bob. The P is the parity check gate shown in Fig.2. It comprises the PBS_1 , charge detector C and PBS_2 . Only Bob needs to perform this concentration.

$$\begin{aligned}
 |\Psi\rangle_{N+1} &= |\Phi\rangle_N \otimes |\Phi\rangle_{b3} = (\alpha|\uparrow\rangle_1|\uparrow\rangle_2\cdots|\uparrow\rangle_N \\
 &+ \beta|\downarrow\rangle_1|\downarrow\rangle_2\cdots|\downarrow\rangle_N) \otimes (\alpha|\downarrow\rangle_{b3} + \beta|\uparrow\rangle_{b3}) \\
 &= \alpha^2|\uparrow\rangle_1|\uparrow\rangle_2|\downarrow\rangle_{b3}\cdots|\uparrow\rangle_N \\
 &+ \beta^2|\downarrow\rangle_1|\downarrow\rangle_2|\uparrow\rangle_{b3}\cdots|\downarrow\rangle_N \\
 &+ \alpha\beta(|\uparrow\rangle_1|\uparrow\rangle_2|\uparrow\rangle_{b3}\cdots|\uparrow\rangle_N + |\downarrow\rangle_1|\downarrow\rangle_2|\downarrow\rangle_{b3}\cdots|\downarrow\rangle_N).
 \end{aligned} \quad (19)$$

Subsequently, the electrons in the spatial modes $b1$ and $b3$ in Bob's location pass through the P gate. If the charge detector's result is $C = 1$, the Eq. (19) will collapse to

$$\begin{aligned}
 |\Psi'\rangle_{N+1} &= \frac{1}{\sqrt{2}}(|\uparrow\rangle_1|\uparrow\rangle_2|\uparrow\rangle_{c2}\cdots|\uparrow\rangle_N \\
 &+ |\downarrow\rangle_1|\downarrow\rangle_2|\downarrow\rangle_{c2}\cdots|\downarrow\rangle_N),
 \end{aligned} \quad (20)$$

with the probability of $2|\alpha\beta|^2$. Finally, Bob performs a Hadamard operation, and measures the electron in the mode $c2$ in the basis $Z = \{|\uparrow\rangle, |\downarrow\rangle\}$. If the measurement result is $|\uparrow\rangle$, they will get

$$\begin{aligned}
 |\Psi'\rangle_N &= \frac{1}{\sqrt{2}}(|\uparrow\rangle_1|\uparrow\rangle_2\cdots|\uparrow\rangle_N \\
 &+ |\downarrow\rangle_1|\downarrow\rangle_2\cdots|\downarrow\rangle_N),
 \end{aligned} \quad (21)$$

and if the measurement result is $|\downarrow\rangle$, they will get

$$\begin{aligned}
 |\Psi''\rangle_N &= \frac{1}{\sqrt{2}}(|\uparrow\rangle_1|\uparrow\rangle_2\cdots|\uparrow\rangle_N \\
 &- |\downarrow\rangle_1|\downarrow\rangle_2\cdots|\downarrow\rangle_N).
 \end{aligned} \quad (22)$$

Both Eqs. (21) and (22) are the N -electron maximally entangled states.

Otherwise, if the charge detector's result is $C = 0$, then Eq. (19) becomes

$$\begin{aligned}
 |\Psi''\rangle_{N+1} &= \alpha^2|\uparrow\rangle_1|\uparrow\rangle_2|\downarrow\rangle_{b3}\cdots|\uparrow\rangle_N \\
 &+ \beta^2|\downarrow\rangle_1|\downarrow\rangle_2|\uparrow\rangle_{b3}\cdots|\downarrow\rangle_N.
 \end{aligned} \quad (23)$$

After performing the Hadamard operation and measuring the electron in $c2$ mode in the Z basis, the above state becomes

$$\begin{aligned}
 |\Psi^\pm\rangle_N &= \alpha^2|\uparrow\rangle_1|\uparrow\rangle_2\cdots|\uparrow\rangle_N \\
 &\pm \beta^2|\downarrow\rangle_1|\downarrow\rangle_2\cdots|\downarrow\rangle_N.
 \end{aligned} \quad (24)$$

Compared with Eq. (18), it is also a multipartite less-entangled state which can be reconcentrated into a maximally entangled state. '+' or '-' is decided by the measurement result $|\uparrow\rangle$ or $|\downarrow\rangle$, respectively.

So far, we have fully described our ECP. It is interesting to compare this protocol with Ref. [43]. In Ref. [43], we resort two copies of less-entangled pairs to perform the concentration. We can get one pair of maximally entangled state with the success probability of $2|\alpha\beta|^2$. In this protocol, we use only one pair of less-entangled state and a single electron which can reach the same success probability with Ref. [43]. Moreover, during the whole protocol, only one-way classical communication is required. That is Alice only needs to receive the information from the Bob's measurement and to judge whether the protocol is successful or fail. If the protocol is a failure, Alice needs to do nothing. If the protocol is successful, Bob will tell Alice the remaining state is $|\phi^+\rangle$ or $|\phi^-\rangle$ according to his measurement. In previous protocols [24, 36, 38, 43], all of the parties have to participate the whole procedure, to measure their electrons and check their results to each other to judge the remained state if the protocol is successful. So this protocol is much more simple, especially when it is used to concentration multi-partite system, for only one of the parties needs to perform the protocol and then report his results to others. Finally, let us briefly discuss the key ingredient of this protocol here, that is charge detector [56–58]. It has been realized in a two-dimensional electron gas. It was reported that currently achievable time resolution for charge detection is μs [57]. In a semiconductor it was reported that the resolution required for ballistic electrons is less than 5 ps [58]. Compared with flying qubit, it may be more practical to use isolated electrons in an array of quantum dots, as pointed by Ref. [47].

In conclusion, we have proposed an mobile electron ECP based on charge detection. Compared with other protocols, it has several advantages: first, it does not require the post-selection principle, and can be repeated to reach a higher efficiency than those based on linear optical elements; second, only one pair of less-entangled state and one-way classical communication are required, which make this protocol more economic and simple than others. All these advantages make this ECP more useful in current quantum communication and distributed quantum information processing.

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